Coupled Thermocline - Deep Ocean Processes in Baroclinic Fronts and Eddies: Towards Improving Model Initialization and Data Assimilation

Isaac Ginis and Georgi Sutyrin
Graduate School of Oceanography
University of Rhode Island
Narragansett RI 02882
phone: (401) 874-6484 and (401) 874-6213 fax: (401) 874-6728
email: iginis@gso.uri.edu and gsutyrin@gso.uri.edu

Award #: N000149710139

LONG-TERM GOAL

Our long-term goal is to achieve a correct understanding of the physical processes at the continental margin interface, including feedbacks between the coastal and open ocean, and to investigate the ability of numerical models to simulate physical processes over continental slope regions.

SCIENTIFIC OBJECTIVES

The specific scientific objectives of this project are focused on studying the dynamical coupling between meandering baroclinic jets and cut off eddies with the deep flow over steep topography. Emphasis is placed on improving our understanding of the life cycle of energetic flow perturbations excited by meandering of baroclinic jets and/or warm-core rings approaching the shelf break from the open ocean. The gained knowledge would allow us developing new model initialization and data assimilation techniques.

APPROACH

Our approach combines theoretical investigation with advanced numerical modeling to gain understanding and efficient representation of the most important physical processes in the littoral zone. In collaboration with the Prof. Watts' (URI) project we use analytical and numerical models for analyses of the SYNOP Central Array data set.

WORK COMPLETED

We have developed a balanced PV-gradient model for initializing a Gulf Stream-type jet with *steep* meanders over topography. The jet is prescribed as a PV front in the upper thermocline overlying intermediate layers with weak PV gradients. The single-layer balanced model of Sutyrin (1994) was generalized for a multi-layer structure to obtain the corresponding density and velocity fields in the jet. Using the new model we investigated *a)* the effects of meander curvature on the structure of a Gulf Stream–type jet and *b)* the asymmetry of the mean flow structure created by deep eddies beneath a meandering jet. We conducted a thorough analysis of different forces in steep meanders on the structure of the stream. Several important tendencies were identified in the structure of the Gulf Stream troughs and crests. A graduate student, Sergey A. Frolov, completed his Ph.D. working on this project (Frolov, 2001).

We have also studied the interaction between a coherent eddy and a vertically sheared baroclinic current, focusing on the ability of the vortex to resist to tearing effects. We have completed an analytical theory for the beta-drift of a surface-intensified vortex over a sloping bottom with an arbitrary orientation.

RESULTS

a. *Velocity and density structure in steep meanders initialized using potential vorticity.*

The balanced PV-gradient model a Gulf Stream-type jet combines the cross-stream layer PV structure derived from historic observational data with the real-time observed stream position assuming along-stream preservation of PV. In addition, a balanced approximation (Sutyrin, 1994) is applied to calculate the Gulf Stream density and velocity structure, which allows for accounting the centrifugal force in steep meanders. For the first time we are able to initialize a baroclinic Gulf Stream-type jet with very steep meanders. We successfully used the PV-gradient model to initialize the Gulf Stream structure in the Princeton Ocean Model. The majority of the simulated features in the model are found to be in a good agreement with the Oleander (Rossby and Gottlib, 1998) and SYNOP (Watts et al., 1995) observational data. In particular, 1) velocity shear on cyclonic and anticyclonic sides of the stream increases/decreases in meander crests/troughs; 2) depth dependencies of changes in the velocity shear are similar; 3) the average velocity peaks at depths (e.g., 400 and 700 meters) are stronger in crests compare to troughs (Fig. 1); 4) both theoretically predicted and observed average surface velocity peaks are nearly the same in crests and troughs.

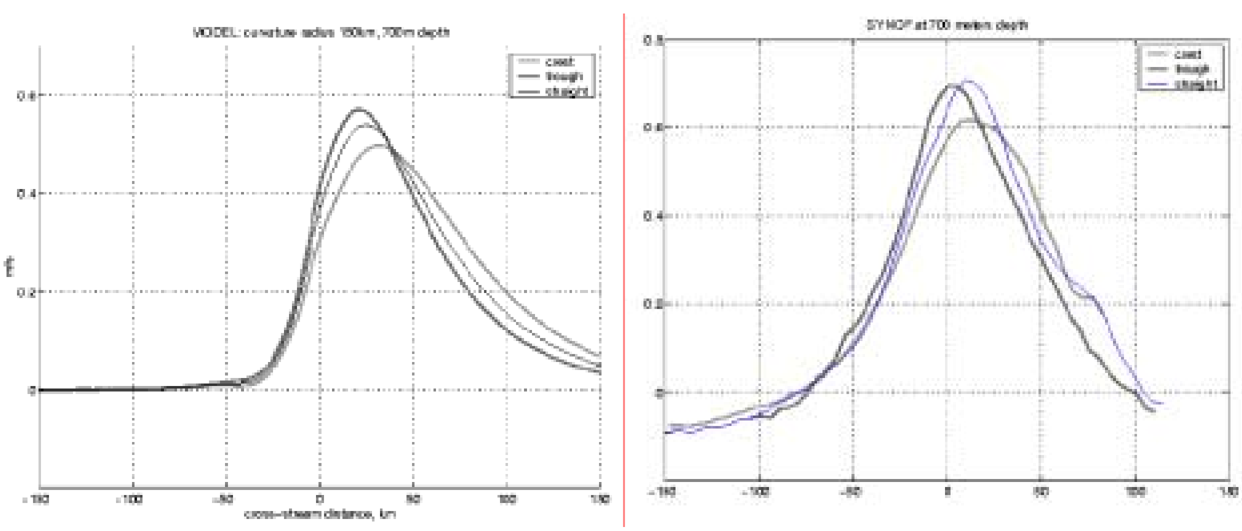

Fig. 1 Average velocity cross-section in meander crests and troughs at 700 m depth: in the balanced PV-gradient model (left panel) and in the SYNOP data (right panel).

b. *Asymmetry of the stabilized Gulf Stream system.*

The properties of the Gulf Stream system downstream of Cape Hatteras were investigated in a series of numerical experiments using Princeton Ocean Model with a sloping bottom. In a typical experiment the Gulf Stream was prescribed as a PV front in the upper thermocline overlying intermediate layers with weak PV gradients and quiescent bottom layer over a bottom topography uniformly sloping in the north-south direction. A small disturbance introduced to the PV front develops into a meander packet growing and propagating downstream (Fig 2). The presence of the bottom slope imposes a limitation on the maximum amplitude of the meanders (Sutyrin et al, 2001). Once the meander packet has reached its maximum amplitude, it continues to propagate downstream leaving behind a stabilized jet. The stabilization occurs due to a nearly barotropic shear associated with two recirculation gyres north and south of the stream formed due to PV mixing by deep eddies associated with meanders.

The meander packet and the recirculation gyres have a distinct asymmetry (Fig. 2). The amplitude of the meander crests is substantially higher than the amplitude of meander troughs. Correspondingly, the magnitude of northern recirculation gyre, as measured by its transport, is larger than the magnitude of the southern recirculation gyre. The above asymmetry appears to be a robust feature in all experiments and nearly independent on the slope steepness in the range 0.0025 – 0.004. The asymmetry of the jet vertical structure, i.e., the lateral shift of the velocity maximum near the surface relative the velocity maximum at depth, is shown to be primarily responsible for the asymmetry of meandering and recirculation gyres. The asymmetry seen in the numerical experiments is consistent with the SYNOP observations.

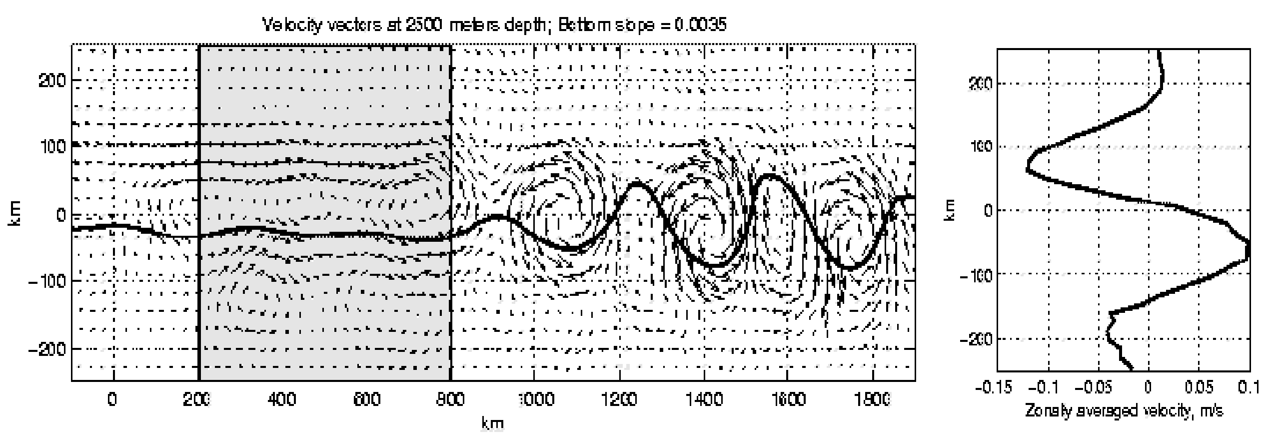

Fig. 2. The jet position (bold line) after 60 days of integration superimposed by the velocity vectors at 2500 m depth (left panel). The shaded area indicates the extent of the zonal averaging. The result of averaging of the zonal velocity component is shown in the right panel.

c. *Resistance of eddies to a vertically sheared current.*

We have analyzed nonlinear interaction of a localized vortex and vertically sheared surrounding flow using asymptotic and numerical methods in a multi-layer quasi-geostrophic model on the beta-plane. The initial vortex structure was prescribed by a circular fluid PV in a three layer model with no motion in the lower layer. The vertical coherence of a baroclinic vortex was found to be much stronger due to the baroclinic beta-effect which was not taken into account in previous studies. Correspondingly, the net advective and tearing effects of vertically sheared flow on a baroclinic vortex are substantially reduced which explains why oceanic rings and meddies are so long-lived.

d. *The topographic effects on the beta-drift of a baroclinic vortex*

An asymptotic theory was used to analyze the evolution of a surface-intensified vortex on the beta-plane over a sloping bottom with an arbitrary orientation. The ring evolution is governed by the planetary beta-effect and deep circulation gyres beneath the drifting ring which are found to be proportional to the *cross-slope* drift speed. These deep gyres produce in additional *along-slope* ring translation which is inverse proportional to the slope. These effects can explain observed southwest propagation of warm-core rings over the continental slope typical for Atlantic Ocean.

IMPACT/APPLICATION

This research has direct implication toward improving our forecast skill of the Gulf Stream and Gulf Stream-type fronts. The means by which we have initialized the Gulf Stream structure and analyzed the evolution of baroclinic meanders and deep eddies over topography in this study are novel and can be used in ocean nowcasting and forecasting. Demonstrated strong vertical coupling between the upper and lower layers in baroclinic jets has an important impact on future strategies for observations, data assimilation and modeling.

New physical mechanisms suggested in this study explaining the observed changes of the baroclinic jet structure in steep meanders and in equilibrated state have implications for our understanding of coupling, horizontal and vertical, of flow over the topography of the continental margin. Resistance of coherent eddies to a vertically sheared current and topographic effects on the beta-drift of baroclinic eddies have not been explained previously.

TRANSITIONS

Our three-pronged work (observations / theory / modeling) in collaboration with the Dr. Watts' project indicates that it is crucial to know the deep eddy current field in order to successfully initialize and predict the evolution of the upper baroclinic front. The balanced PV-gradient model is mature enough to be implemented for modeling and forecasting of the Gulf Stream at NRL. The new understanding and technology developed in this project will benefit present observational and model studies in the Japan/East Sea jointly conducted by URI and NRL and future collaborations with NRL in the Gulf of Mexico.

RELATED PROJECTS

Dr. Randy Watts (URI) uses the PV-gradient model developed in this project for analysis of the observed velocity and density structures during the SYNOP field experiment. Drs. Isaac Ginis and Lew Rothstein (URI) use the PV initialization approach for modeling hurricane - ocean interaction. Drs. Yves Morel (SHOM, France) and Georgi Sutyrin (URI) use asymptotic methods developed in this project to investigate vortex interaction with a vertically sheared surrounding flow. Drs. Gregory Reznik (IORAS, Russia) and Georgi Sutyrin (URI) analyze mutual effects of topography and baroclinicity on long-lived vortices to improve our understanding of vertical coupling over a sloping bottom.

REFERENCES

Rossby, H., and E. Gotlieb, 1998: The Oleander project: Monitoring the variability of the Gulf Stream and adjacent waters between New Jersey and Bermuda. *Bulletin of the AMS*, **79**, 5-18.

Sutyrin, G.G., 1994: Long-lived planetary vortices and their evolution: conservative intermediate geostrophic model. *Chaos*, **4**, 203-212.

Watts, D. R., K. L. Tracey, J. M. Bane, and T. J. Shay, 1995: Gulf Stream path and thermocline structure near 74°W and 68°W, *J. Geophys. Res.,* **18**, 18,291-18,312.

PUBLICATIONS

Frolov, S.A., 2001: Modeling of the Gulf Stream system. Ph.D. University of Rhode Island.

Frolov, S.A., Sutyrin, G.G., and I. Ginis, 2001: Asymmetry of the stabilized Gulf Stream system. Submitted to *J. Phys Oceanogr*.

Logoutov, O.G., Sutyrin, G.G., and D.R. Watts, 2001: Potential vorticity structure across the Gulf Stream: Observations and a PV-gradient model. *J. Phys Oceanogr*. **31**, 637-644.

Sutyrin, G.G., 2001: The effects of topography on the beta-drift of a baroclinic vortex. *J. Mar. Res*., in press.

Sutyrin, G.G., I. Ginis, and S.A. Frolov, 2001: Equilibration of the Gulf Stream meanders and deep eddies over a sloping bottom. *J. Phys. Oceanogr.*, **31,** 2049-2065.

Sutyrin, G.G., S.A. Frolov, and I. Ginis, 2001: Stabilization of a baroclinic jet over topography. *26th General Assembly of the European Geophysical Society, Geophys. Res Abs.* **3**.

Sutyrin, G.G., I. Ginis, and S.A. Frolov, 2001: Nonlinear equilibration of a baroclinically unstable jet over topographic slope. *Proceedings of the IUTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics*, (P.F.Hodnett, Ed.), Kluwer Academic Publishers, 245-250.

Vandermeirsh, F.,Y. Morel, and G.G. Sutyrin, 2001: The net advective effect of a vertically sheared current on a coherent vortex. *J. Phys. Oceanogr*., **31,** 2210-2225.

Vandermeirsh, F., Y. Morel, and G.G. Sutyrin, 2001: Resitance of a coherent vortex to a vertically sheared current. Submitted to *J. Phys. Oceanogr.*

Vandermeirsh, F., Y. Morel, and G.G. Sutyrin, 2001: The role of a baroclinic β-effect in vortex tearing by a vertically sheared current. *26th General Assembly of the European Geophysical Society, Geophys. Res. Abs.* **3**.